RECENT RESULTS ON HADRONIC PHYSICS FROM BELLE AND PROSPECTS AT BELLE II

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For the Belle & Belle II Collaborations
HADRONIC PHYSICS IN $e^+e^-$ B FACTORIES

- Study of the formation of hadrons → e.g. Phys. Rev. D97 (2018) no.7, 072005
- Study of hadronization, microscopic quark properties ↔ macroscopic hadron properties
  - Relativistic, non-perturbative QCD dynamics → Fragmentation functions
- Study of the produced hadrons, spectroscopy
Belle (II) detector
KEKB
BELLE EXPERIMENT (1999 - 2010)

Belle Detector

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Scans/Off. Res. fb$^{-1}$</th>
<th>$\Upsilon$(5S) 10076 MeV $10^6$</th>
<th>$\Upsilon$(4S) 10580 MeV $10^6$</th>
<th>$\Upsilon$(3S) 10355 MeV $10^6$</th>
<th>$\Upsilon$(2S) 10023 MeV $10^6$</th>
<th>$\Upsilon$(1S) 9460 MeV $10^6$</th>
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<td>17.1</td>
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<td>16</td>
<td>17.1</td>
<td>1.2</td>
<td>5</td>
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<td>54</td>
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+About 4x10$^6$ events per fb in continuum
**KEKB → SUPERKEKB: DELIVER INSTANTANEOUS LUMINOSITY X 40**

**Belle II**

**e^+ 4GeV 3.6 A**

**e^- 7GeV 2.6 A**

(~2x KEKB)

**SuperKEKB**

**Target:** $L = 8 \times 10^{35}/\text{cm}^2/\text{s}$

- **New superconducting final focusing quads (QCS) near the IP**
- **Reinforce RF systems for higher beam current**
- **New positron target / capture section**
- **New IR**
- **Nano beam collision**
- **Damping ring (new)**
- **Replace short dipoles with longer ones**
- **Redesign the lattices of HER & LER to squeeze the emittance**
- **TiN-coated beam pipe with antechambers Cu for wigglers and Al alloy for the rest**
- **To inject low emittance electrons**
- **To inject low emittance positrons**

**Formula:**

$$L = \frac{\gamma_s}{2e_r} \left( \frac{O_y^2}{I_y} \right) \frac{\beta_y^2}{R_y}$$

**KEKB à SUPERKEKB: DELIVER INSTANTANEOUS LUMINOSITY X 40**
BELLE II DETECTOR (COMP. TO BELLE)
26 APRIL 2018 00:38 GMT+09:00: FIRST COLLISIONS
CURRENT STATUS AND SCHEDULE

• Phase 1 (complete)
  • Accelerator commissioning

• Phase 2 (now)
  • First collisions ($20\pm20$ fb$^{-1}$)
  • Partial detector
  • Background study
  • Physics possible

• Phase 3 (“Run I”, early 2019)
  • Nominal Belle II start

• Ultimate goal: $50$ ab$^{-1}$

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Goal of Belle II/SuperKEKB

- Integrated luminosity (ab$^{-1}$)
- Peak luminosity (cm$^{-2}$s$^{-1}$)
- Calendar Year

- 9 months/year
- 20 days/month
FRAGMENTATION FUNCTIONS WITH ADDITIONAL DEGREES OF FREEDOM: NOVEL PROBES OF THE NUCLEON STRUCTURE AND HADRONIZATION

• Di-hadron fragmentation functions
• Polarized Hyperons
DI-HADRON FRAGMENTATION FUNCTIONS

• Additional degree of freedom ($\vec{R} = \vec{P}_1 - \vec{P}_2$)
  • Plus $z, p_T$

• Relative momentum of hadrons can carry away angular momentum
  • Partial wave decomposition in $\theta$
  • Relative and total angular momentum $\rightarrow$ In principle endless tower of FFs
  • Analogue of $1h$ production with spin in final state

• Transverse polarization dependence in collinear framework
  • Makes ‘new’ FFs possible, such as $G_1^\perp : T$-odd chiral even. In $1h$ case, this needs polarized hadron in the final state $\rightarrow$ See H. Matevosyan’s talk!

• Similar to $A$ FF, chiral-even, $T$-odd: Important to check factorization
EXAMPLE, ACCESS OF $e(x)$ IN SIDIS X-SECTION

- Di-hadron cross section

$$F_{\text{LU}}^{\sin \phi_r} = -x \frac{R}{Q} \sin \theta \left[ \frac{M}{m_{hh}} x e^q(x) H_1^q(z, \cos \theta, m_{hh}) + \frac{1}{z} f_1^q(x) \tilde{G}^q(z, \cos \theta, m_{hh}) \right],$$

- Single hadron cross-section: mixes other contributions:

$$F_{\text{LU}}^{\sin(\phi_h)} = \frac{2M_T}{Q} \left[ -\frac{k_T P_{h\perp}}{M_h} \left( x e H_1^\perp + \frac{M_h}{M_z} f_1 \tilde{G}^\perp \right) \right] + \frac{p_T P_{h\perp}}{M} \left( x g^\perp D_1 + \frac{M_z}{M} h_1^\perp \tilde{E} \right) \right]$$
RECENT BELLE RESULT

Low $z$: Dominated by PID uncertainties
Belle II prospects: Improved PID, higher statistics to improve uncertainties on PID

High $z$: Dominated by ISR uncertainties
Belle II prospects: better understanding of ISR radiation with better statistics

BELLE II PROSPECTS

- Partial Wave decomposition (more general: \( \theta \) dependence)
- Higher order PWs lead to different moments in \( \theta \) and \( \phi \)
- In models, evolution of the different PWs different
- Important to have a full picture to understand mixing effects in ratios/partial integrals/acceptance
- Missing info from partial wave estimated to have effects up to 10% e.g. on extraction of transversity
Belle II prospects: Sufficient statistics for full partial wave decomposition
POLARIZED HYPERON PRODUCTION

- Large $\Lambda$ transverse polarization in unpolarized $pp$ collision \textbf{PRL36, 1113 (1976); PRL41, 607 (1978)}

- Caused by polarizing FF $D_{1T}^\uparrow(z, p_L^2)$?

- Polarizing FF is chiral-even, has been proposed as a test of universality. \textbf{PRL105,202001 (2010)}

- OPAL experiment at LEP has studied transverse $\Lambda$ polarization, no significant signal was observed. \textbf{Eur. Phys. J. C2, 49 (1998)}

- FF counterpart of the Sivers function.

\[ x_F = p_L / \max p_L \sim \text{LO} x_1 = x_2 \sim \text{forward} x_1 \]
• Polarization rises with $p_T$ in the lowest $z_\Lambda$ and highest $z_\Lambda$ bin. But the dependence reverses around 1 GeV in the intermediate $z_\Lambda$ bins \textbf{Unexpected!} (might be related to fragmenting quark flavor dependence on $z_1, z_2$)

• Correlation with opposite hemisphere light meson → quark flav/charge dependence
BELLE II PROSPECTS

• Explore low pT region with higher statistics and better tracking resolution
• Feed down correction for pT dependence and associated production
  • (currently only for z dependence, introduces large uncertainties)
  • \( \Lambda ^\uparrow - \Lambda ^\uparrow \) correlations
  • ....

Y. Guan, arXiv:1611.0668
BELLE LEGACY IN HADRONIC PHYSICS – QUARKONIUM (-LIKE) PRODUCTION

• B decays
  • Charmonium only
  • All quantum numbers available

• Direct production / Initial State Radiation (ISR)
  • $E_{CM}$ or below
  • $J^{PC}=1^{--}$

• Two-photon interaction
  • $J^{PC}=0^{-+}, 0^{++}, 2^{++}$

• Double charmonium production
  • Seen for $J^{PC}=1^{--}$ ($J/\psi, \psi(2S)$) plus $J=0$ states ($C=1?$)

• Quarkonium transitions
  • Hadronic/radiative decays between states
QUARKONIUM STUDIES AT BELLE II BUILD ON THE SUCCESSFUL BELLE PROGRAM

• XYZ revolution kicked off by discovery of \( X(3872) \) at Belle 2003
• Strong violation of isospin symmetry in decays \( \rho J/\psi , \omega J/\psi \)
• More states not consistent with quarkonium, usually higher than expected transitions to lower quarkonia.
• Precision study of Charmonium: States above the DDbar threshold are a strongsuit of B factories \( \rightarrow \) can access energy spectrum continuously)
• Precision studies of Bottomium states and transitions

(Choi et al, PRL 91 (26) 262001)
Z: EVIDENTLY EXOTIC, NEEDS 4 QUARKS

- APS highlight 2013

Further 4-quark-configurations:

- Hybrid \((q\bar{q})_8 g\)
- Tetraquark \((qqqq)_1\)
- Glue-ball \((gg)_1\) or \((ggg)_1\)
- Molecule \((q\bar{q})(q\bar{q})_1\)
- Hadro-quarkonium \((QQ)(q\bar{q})_1\)
- Di-quarkonium \((qq)(q\bar{q})_3\)
Recent Spectroscopy Results

- Phys. Rev. D 95, 112003 (2017) **Observation of an alternative \( \chi_{c0}(2P) \)** candidate in \( e^+e^- \rightarrow J/\psi DD^- \)
- Phys. Rev. D 97, 012002 (2018) **Angular analysis of the** \( e^+e^- \rightarrow D(*)\pm D^* \mp \)** process near the open charm threshold using initial-state radiation
- Phys. Rev. D 97, 012005 (2018) **Measurements of the absolute branching fractions of** \( B^+ \rightarrow X_{cc} K^+ \) and \( B^+ \rightarrow D^- (\ast)0\pi^+ \) at Belle
- Phys. Rev. D 96, 051102 (2017) **Search for** \( \Lambda^+c \rightarrow \phi\pi\pi \) and branching fraction measurement of \( \Lambda^+c \rightarrow K^-\pi^+\pi\pi \)
- Phys. Rev. D 95, 012001 (2017) **Search for the** \( 0^- \) **Glueball in** \( \Upsilon(1S) \) and \( \Upsilon(2S) \) decays
  - Phys. Rev. D 96, 052005 (2017) **Study of** \( \eta \) and dipion transitions in \( \Upsilon(4S) \) decays to lower bottomonia
- Phys. Rev. D 96, 112002 (2017) **Search for light tetraquark states in** \( \Upsilon(1S) \) and \( \Upsilon(2S) \) decays
WISHLIST

- More data will help Quarkonium
  - Map out resonances
  - Can reach Y(6S) with same boost as Y(4S)
  - More data at/above Y(4S) → search molecular structures near open bottom thresholds
  - Experimental information of charmonium > Ddobar threshold very incomplete,
  - More data below Y(4S) → test predictions for unobserved bottomium states
  - Determine transitions and quantum numbers
  - Precision scans of bottomium sector, comparison with charmonium states should shed light on some properties (spin symmetry suppression not as strong)
  - Need enough data for amplitude analysis to check if found states are the expected ones
BELLE II EARLY PHYSICS PROSPECTS

- Existing B-Factories ~1.5 ab⁻¹: opportunity for other results in Phase 2/3?

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Potential impact with \( \mathcal{O}(10-100) \) fb⁻¹

- Early phase 3: Above \( \Upsilon(4S) \)
  - Study of \( \Upsilon(nS) \) states in (hadronic) transitions
  - Study of exotic four-quark states (e.g. \( Z_b \) at \( \Upsilon(6S) \))
  - BB** threshold? : \( R_b \) dip versus \( \pi\pi \Upsilon \) rise

\[ \text{Phys. Rev. Lett. 117 (2016) no.14, 142001} \]
SUMMARY & OUTLOOK

- Belle II will integrate 50x Belle luminosity (= 50 ab⁻¹) over ~6 years
- State of the art detector
- Precision studies of Quarkonia, hadronization
- Physics program with first data focusing on $E_{CM} > Y(4S)$ already promising!
- Precision hadronization studies crucial for JLab12 SIDIS program
BACKUP
BELLE II EARLY PHYSICS PROSPECTS

- Existing B-Factories ~1.5 ab⁻¹: opportunity for other results in Phase 2/3?

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- Phase 2: Above $\Upsilon(4S)$
  - Study of exotic four-quark states (e.g. Zb at $\Upsilon(6S)$)
    → Study possible with limited tracking resolution
  - BB** threshold? : $R_b$ dip versus $\pi\pi\Upsilon$ rise
  - <6fb⁻¹ accumulated by Belle at $E_{CM}=\Upsilon(6S)$

- Early phase 3: Below $\Upsilon(4S)$
  - $\Upsilon(2S,3S)$ access to bottomonium
  - Scan for direct production of $\Upsilon(1^3D_J)$ triplet, $\eta_b(1S,2S)$ studies

PRD 82, 091106 (2010). 0810.3829. (Belle)
OTHER PERKS

- More statistics and better vertexing will help with charm corrections
- Systematics will also be reduced since the main sources are dependent on MC statistics
- Better PID will help with multi-kaon final states

PID performance

Transverse polarization
Dependent di-hadron
Asymmetries in e+e- from Belle

Charm vs uds in b2b kaon production (likesign)

~45% uds
PRODUCTION OF CHARMED AND NON CHARMED BARYONS

- $\Xi^{-}, \Xi(1530), \Omega^{-}, \Sigma_c, \Omega_c, \Xi_c$ not shown
MASS DEPENDENCE CONFIRMS DIQUARK MODEL

![Graphs showing mass dependence and confirmations for diquark model.](image-url)
OUTLINE

• Belle (I) Legacy
  • Quarkonium (like)
  • Hadronization (Fragmentation function measurements)

• SuperKEKB and Belle II
  • Upgrade
  • Status
  • Early Physics program
  • Outlook
BACKGROUND UNFOLDING

- \( \Sigma^* \) decays to \( \Lambda \) strongly, is included in the signal.
- Feed-down from \( \Sigma^0 (22.5\%) \), \( \Lambda_c (20\%) \) decays need to be understood.
- The \( \Sigma^0 \)-enhanced (\( \Sigma^0 \rightarrow \Lambda + \gamma \)) (Br\( \sim \)100\%). and \( \Lambda_c \)-enhanced (\( \Lambda_c \rightarrow \Lambda + \pi^+ \)) (Br\( \sim \)1.07\%) data sets are selected and studied.
- The measured polarization can be expressed as:

\[
P_{\text{mea.}} = (1 - \sum_i F_i) P_{\text{true}} + \sum_i F_i P_i,
\]

- \( F_i \) is the fraction of feed-down component \( i \), estimated from MC. \( P_i \) is polarization of component \( i \).
- Polarization of \( \Lambda \) from \( \Sigma^0 \) decays is found has opposite sign with that of inclusive \( \Lambda \).

Before there was KEKB: asymmetric $e^+ (3.5 \text{ GeV})$ $e^- (8 \text{ GeV})$ collider:

\[ \sqrt{s} = 10.58 \text{ GeV}, \quad e^+e^- \rightarrow Y(nS) \rightarrow B/B + \text{continuum} \]

\[ \sqrt{s} = 10.52 \text{ GeV}, \quad e^+e^- \rightarrow \text{qqbar} \ (u,d,s,c) + \text{continuum} \]

- Ideal (at the time) detector for high precision measurements:
  - tracking acceptance $\theta [17^\circ;150^\circ]$: Azimuthally symmetric
  - particle identification (PID): $dE/dx$, Cherenkov, ToF, EMcal, MuID

- Available data:
  - $\sim 1 \text{ ab}^{-1}$ total
  - $\sim 1.8 \times 10^9$ events at 10.58 GeV,
  - $\sim 220 \times 10^6$ events at 10.52 GeV

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(took data till 2010)
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